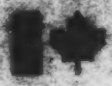
ERB-946

NRCC No. 23590



National Research Council Canada
Conseil national de recherches Canada

Division of Electrical Engineering
Division de génie électrique

A PRELIMINARY STUDY OF THE PERFORMANCE CHARACTERISTICS OF PHOTOVOLTAIC MODULES

J. AYER, R. WRIGHT AND P. GARIÉPY

SEPTEMBER 1984

Canada

85-3213/

Copyright 1984 by
National Research Council of Canada

Permission is granted to quote short excerpts and to reproduce figures and tables from this report, provided that the source of such material is fully acknowledged.

A PRELIMINARY STUDY OF THE PERFORMANCE CHARACTERISTICS OF PHOTOVOLTAIC MODULES

J. Ayer, R. Wright and P. Gariépy

ERB-968
NRCC No. 23590

SEPTEMBER 1984

TABLE OF CONTENTS

	Page
ABSTRACT/RÉSUMÉ	v
INTRODUCTION	1
OBJECTIVE	1
EXPERIMENTAL FACILITIES	4
The Solar Mini-lab	4
Data Acquisition	4
THEORY	5
TEST RESULTS	5
Material Imperfections	10
Measurement of Global Solar Radiation	11
Module Power Output	14
OBSERVATIONS	21
Canadian	22
American	23
CONCLUDING REMARKS	23
ACKNOWLEDGEMENTS	24
REFERENCES	24
APPENDIX A. Test Facility Components	25
Appendix B. Nominal Accuracy of the Measuring Instruments	27

LIST OF FIGURES

1	Solar mini-lab sun surface geometry	2
2	Operational test set-up for photovoltaic modules	3
3	Practical solar cell model	8
4	Insolation and ambient temperature dependence of a PV module	8
5	Typical performance curves of silicon PV modules - power output/temperature	9
6	Spectral response of a silicon solar cell	9
7	Power utilization considerations - one day operation in terrestrial environment	10
8	Mean monthly values of daily short wave radiation on 0° aspect-angle and 0° and 60° tilt angles for Ottawa (1957-1975).	11
9	Mean monthly values of daily short wave radiation on 0° aspect-angle and 0° and 60° tilt angles for Ottawa from Aug. 1982 to July 1983	12
10	Ratio of mean monthly values of daily short wave radiation on horizontal to 60° tilt-angle surface for Ottawa	12
11	Monthly average energy output of a Canadian manufactured PV module in Ottawa	20
12	Monthly average energy output of an American manufactured PV module in Ottawa	20

LIST OF TABLES

		Page
1	Typical daily data report (for July 5, 1983)	6
2	Table for Fig. 8	13
3	Table for Fig. 9	14
4	Table for Fig. 10	15
5	Module physical characteristics	17
6	Module operational characteristics at beginning and end of test period	18
7	Table for Figs. 11 and 12	21

ABSTRACT

Since 1981, the Division of Electrical Engineering, National Research Council, Montreal Road, has been measuring the performance characteristics of about 46 silicon (single crystal) photovoltaic modules (39 Canadian and 7 of American manufacture) in the Ottawa area environmental conditions. Insolation, temperature, module power output, and other parameters were logged into a data acquisition system and later the data were processed and analysed. The results indicate a progressive improvement in performance of Canadian-made photovoltaic modules.

RÉSUMÉ

Depuis 1981, la Division de génie électrique du Conseil national de recherches, chemin de Montréal, évalue les particularités de rendement d'environ 46 modules photovoltaïques au silicium (monocristal) (39 de fabrication canadienne et 7 de fabrication américaine) dans les conditions environnementales de la région d'Ottawa. Des données sur l'insolation, la température, la puissance fournie par chaque module et autres paramètres ont été consignées dans le système de saisie de données et, par la suite, ces données ont été traitées et analysées. Les résultats indiquent une amélioration progressive du rendement des modules photovoltaïques fabriqués au Canada.

A PRELIMINARY STUDY OF THE PERFORMANCE CHARACTERISTICS OF PHOTOVOLTAIC MODULES

J. Ayer, R. Wright, and P. Gariépy

INTRODUCTION

Canadian-made photovoltaic (PV) modules began to be commercially available in Canada in the late 1970's. The study was essentially to obtain practical test experience of the characteristics of the device, especially its electrical performance as an active component in a power generating system.

Forty-six photovoltaic modules were purchased, some in early 1980 and others later as new models came on the market from the three Canadian and four leading American companies. The modules are mounted on the roof of Building M-50, National Research Council, Ottawa, Ontario, as shown in Figs. 1 and 2. Daily measurements of various parameters both of the modules and the environment are logged by a data acquisition system and then later processed. The data measured during the tests and those calculated based on the measured values are fully described.

Nomenclature:

avg	- average
d	- day
MJ	- megajoules (10^6 J)
m/s	- metre per second
MV60avg	- average monthly value at 60° tilt-angle
MVHavg	- average monthly value at horizontal
MVOPavg	- average monthly value at optimum tilt-angle
W/m^2	- watts per square metre
Wp	- peak watts
µm	- micrometre

OBJECTIVE

The objective of this study was to measure the electrical characteristics of the PV module, e.g., open circuit volts (V_{oc}), short circuit current (I_{sc}), series resistance (R_s), shunt resistance (R_{sh}), and voltage and

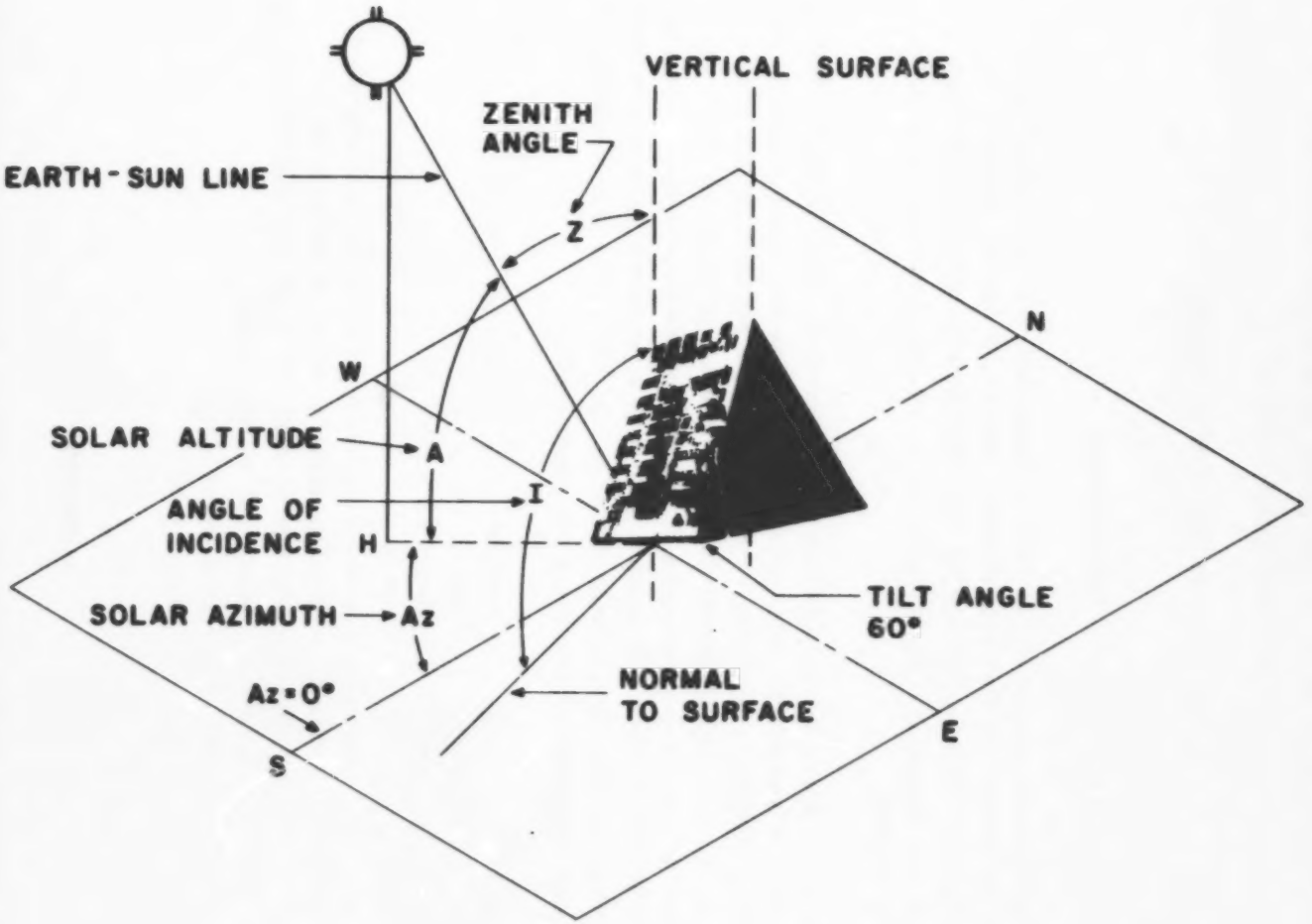


Fig. 1. Solar mini-lab sun surface geometry

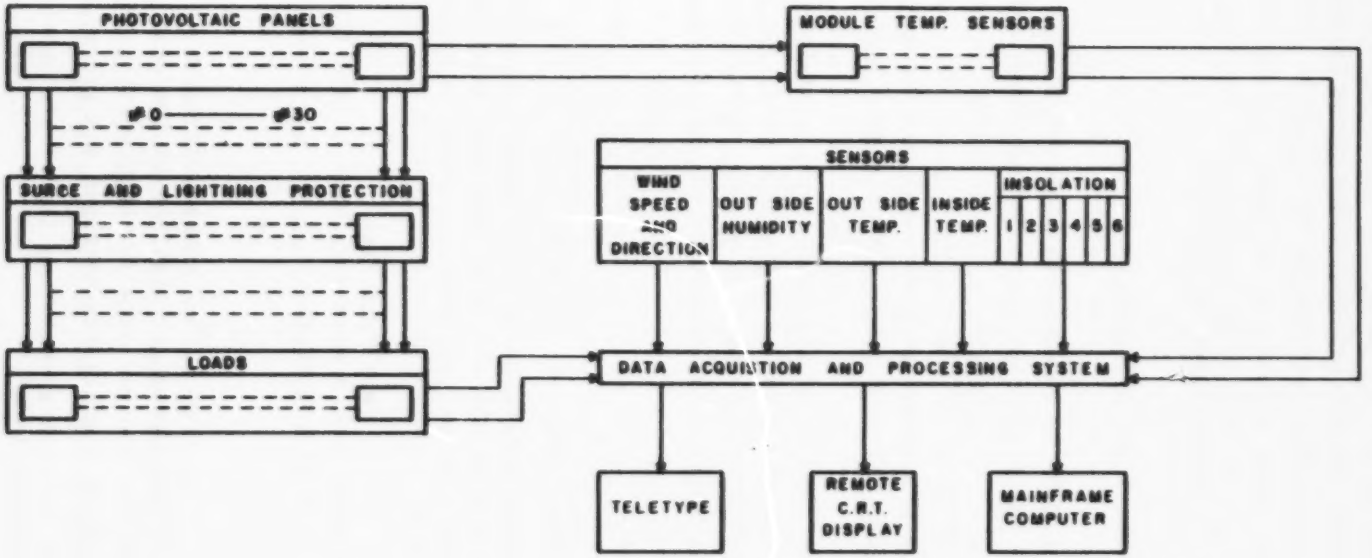


Fig. 2. Operational test set-up for photovoltaic modules

current at maximum power point (V_m and I_m, respectively), all under varying conditions of temperature and insolation. These characteristics provide the design basics for PV power conditioning units and PV power systems.

EXPERIMENTAL FACILITIES

The Solar Mini-lab (Figs. 1 and 2)

As shown in Fig. 1, the solar mini-lab consists of an A-frame cabin mounted on the roof of Building M-50 in the NRC complex. Its features are

- roof area ~192 ft^2 (~17.84 m^2)
- roof angle 60° with respect to horizontal and facing true South
- inside volume 1000 ft^3 (~28.3 m^3) with air conditioning

The PV modules are mounted on the roof of the mini-lab on a frame of tubular steel. A part of the frame is adjustable up to 90° with respect to horizontal for varying tilt-angle tests on single modules. The modules were tested at 60° tilt-angle with respect to the horizontal.

The mini-lab houses

- variable resistive loads for each module
- a data acquisition system
- signal transducer circuits for measuring insolation (horizontal and 60°), temperature (ambient and module), relative humidity, wind speed and direction

Some of the transducer electronics were developed at NRC (Appendix A); others were purchased from manufacturers.

Data Acquisition

Because of the inherent design limitations of the data acquisition system, it is programmed to log the data for each working day from 08:30 to 16:00 hours. The following signals are measured and logged every 10 min:

- horizontal insolation (W/m^2)
- 60° tilt angle insolation (W/m^2)
- module temperature (°C) (on the back plane of only certain modules)
- ambient temperature (°C)

- relative humidity (%)
- wind speed (m/s) and direction

The data are then transferred to a minicomputer and processed to produce the daily printout. A typical daily printout is shown in Table 1.

THEORY

A solar photovoltaic cell (or module) can be visualized as a variable power source which has electrical, mechanical, and optical characteristics that are affected by intensity of illumination and temperature. The cell or module can be characterized either as a dc or an ac model (1). Some of the characteristics of a single crystal silicon cell are shown in Figs. 3 to 7. During a "real-life" cycling operation, the modules are subjected to the following environmental conditions:

- ambient temperature variation
- relative humidity variation
- wind pressure loading
- mechanical stresses
- hail impact
- rain

These environmental conditions are generally specified in detail for module qualification tests (2).

TEST RESULTS

Due to the nature and length of the tests the results are categorized as:

- material imperfections found in the modules
- NRC short term insolation measurement accuracy compared to Hay's (3) long term measurements
- the physical characteristics of the modules tested
- the day-to-day electrical performance of the modules during the whole test period
- the comparison of an American- and Canadian-made module of similar power output rating and under identical test conditions

Table 1. Typical daily data for July 5, 1983

(1) Roof panel number	(2) Company[a]	(3) Total cell area (m^2) (calc)	(4) Rated power[b] (W) at 1000 W/m^2 at ambient temp. (°C)[c]	(5) Time (a.m.)	(6) Ext. amb. temp. (°C)	(7) NRC insolation (W/m^2) at 60° tilt	(8) Max. voltage (V)	(9) Max. current (A)	(10) Load resistance (Ω)	(11) Max. power[d] (W)	(12) Current per cell area (A/cm^2)	(13) Percentage of rated power[e]
0	C - c1	0.1459	14.40/28°	11:55	24	917	12.6	0.74	17.1	9.3	0.018	64.5
1	A - a1	0.1642	18.00/28°	11:55	24	917	14.9	0.95	15.7	14.1	0.021	78.3
2	A - a2	0.1642	18.00/28°	11:55	24	917	13.6	0.96	14.1	13.1	0.021	73.1
3	U - m1	0.2837	37.00/25°	11:55	24	917	15.3	2.06	7.4	31.6	0.025	85.5
4	A - a3	0.1642	18.00/28°	11:55	24	917	14.3	0.83	17.2	11.9	0.018	65.9
5	C - c2	0.1459	14.40/28°	11:55	24	917	11.7	0.59	19.9	6.9	0.015	48.2
6	U - q	0.1642	23.40/28°	11:55	24	917	16.6	1.12	14.9	18.5	0.024	79.1
7	C - c3	0.1459	14.40 -	11:55	24	917	15.3	0.71	21.5	10.9	0.018	75.9
8	C - c4	0.1459	14.40 -	11:55	24	917	11.0	0.51	21.7	5.6	0.013	38.9
9	B - b1	0.1642	18.00 -	11:55	24	917	13.0	0.84	15.4	11.0	0.019	61.0
10	B - b2	0.1459	18.00 -	11:55	24	917	13.0	1.05	12.4	13.6	0.023	75.5
11	B - b3	0.1459	18.00 -	11:55	24	917	13.4	1.01	13.3	13.5	0.022	75.0
12	B - b4	0.1459	18.00 -	11:55	24	917	12.3	0.99	12.5	12.1	0.022	67.4
13	B - b5	0.1459	18.00 -	11:55	24	917	12.9	1.06	12.1	13.7	0.023	76.0
14	B - b6	0.1459	18.00 -	11:55	24	917	12.4	1.03	12.1	12.7	0.023	70.5
15	U - m2	0.2837	37.00/28°	11:55	24	917	15.7	2.07	7.6	32.4	0.026	87.5
16	B - b7	0.1459	18.00 -	11:55	24	917	11.9	0.93	12.8	11.1	0.020	61.9
17	B - b8	0.1459	18.00 -	11:55	24	917	12.4	1.05	11.8	13.0	0.023	72.2
18	A - a4	0.1642	18.00 -	11:55	24	917	14.5	0.97	14.9	14.1	0.021	78.3
19	U - p1	0.2827	35.00/28°	11:55	24	917	16.6	1.85	9.0	30.6	0.023	87.4
20	U - p2	0.2827	35.00/28°	11:55	24	917	16.6	1.81	9.1	30.3	0.022	86.6
21	A - a5	0.1642	18.00/28°	11:55	24	917	14.7	0.95	15.4	14.0	0.021	77.7
22	B - b9	0.1642	18.00 -	11:55	24	917	15.1	0.81	18.7	12.2	0.018	67.7
23	U - m1	0.2601	34.00/25°	11:55	24	917	13.7	1.46	9.3	20.2	0.020	59.4

Table 1 (Concluded)

(1) Roof panel number	(2) Company[a]	(3) Total cell area (m^2) (calc)	(4) Rated power[b] (W) at 1000 W/m^2 at ambient temp. (°C)[c]	(5) Time (a.m.)	(6) Ext. amb. temp. (°C)	(7) NRC insolation (W/m^2) at 60° tilt	(8) Max. voltage (V)	(9) Max. current (A)	(10) Load resistance (Ω)	(11) Max. power[d] (W)	(12) Current per cell area (A/cm^2)	(13) Percentage of rated power[e]
24	U - a2	0.2601	34.00/25°	11:55	24	917	14.7	1.53	9.6	22.5	0.021	66.1
25	C - c5	0.1459	14.40/28°	11:55	24	917	12.5	0.71	17.6	8.9	0.017	61.8
26	C - c6	0.1459	14.40 -	11:55	24	917	12.9	0.70	18.5	9.0	0.017	62.5
27	B - b14	0.2837	36.00/28°	11:55	24	917	15.3	1.95	7.8	30.0	0.024	83.3
28	A - a6	0.2837	32.00/28°	11:55	24	917	15.5	1.71	9.0	26.7	0.022	83.4

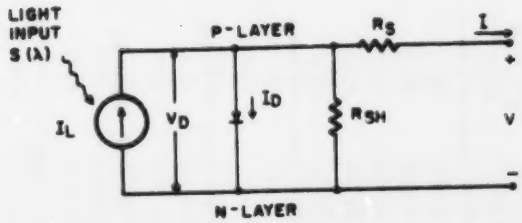
[a] A, B, and C - Canadian; U - American.

[b] In column 4, the rated power output of modules are the manufacturer's figure. In some cases, the test spectrum - sun or simulator and/or temperature - cell or ambient were not defined by the makers.

[c] For panel numbers 19 and 20 the temperatures given by the makers are for cell temperature. For panels where no test temperatures are given, an ambient of 28°C is assumed for test purposes.

[d] In column 11, the maximum power output is calculated from the values of the maximum voltage (column 8) and the load resistance (column 10) at the specified insolation (column 7) and ambient temperature (column 6).

[e] In column 13, the percentage of the rated power is based on the ratio of column 4 and column 11. No corrections for insolation and temperature levels have been made. The percentage figures are for daily qualitative checks only.



THE OUTPUT CURRENT I OF THE CELL

$$I = I_L - I_O \left\{ \exp\left[\frac{e(V + I R_S)}{A k T} \right] - 1 \right\} - \frac{V}{R_{SH}}$$

WHERE

A = AN ARBITRARY CURVE-FITTING CONSTANT BETWEEN 1 AND 5

R_S = CELL'S SERIES RESISTANCE

R_{SH} = CELL'S SHUNT RESISTANCE

I = CELL'S OUTPUT CURRENT

I_L = LIGHT-GENERATED CURRENT

I_O = DIODE SATURATION CURRENT

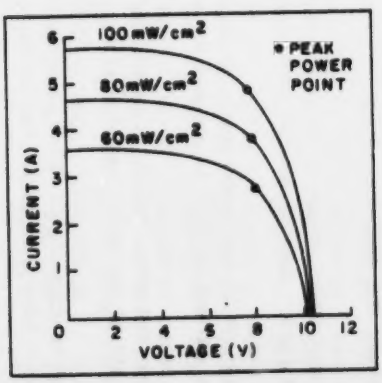
e = ELECTRONIC CHARGE

V = CELL'S TERMINAL VOLTAGE

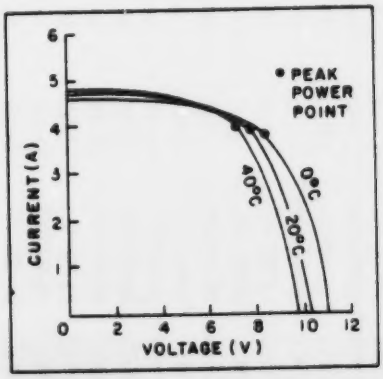
k = BOLTZMANN'S CONSTANT

T = ABSOLUTE TEMPERATURE

Fig. 3. Practical solar cell model (after "Solar Cell Array Design Handbook, Vol. I (1), Fig. 9.2-1)



INSOLATION DEPENDENCE (@TAMBIENT = 25°C)



AMBIENT TEMPERATURE (@80 mW/cm²)

Fig. 4. Insolation and ambient temperature dependence of a PV module (after brochure from Mobil Tyco Solar Energy Corporation (4))

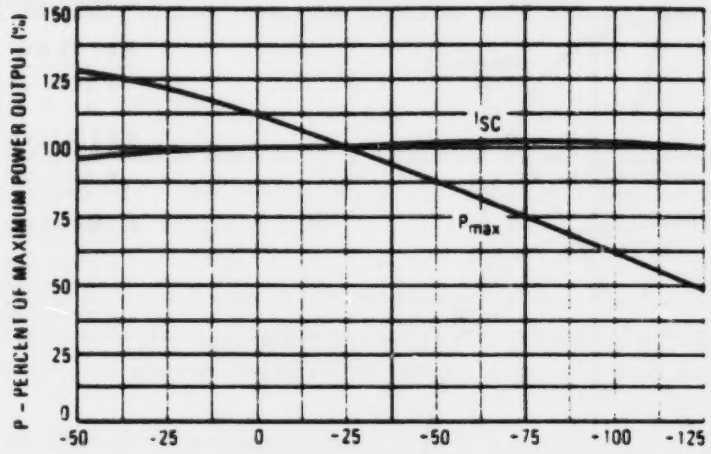


Fig. 5. Typical performance curves of silicon PV modules - power output/temperature. Note: Case temperature is typically 20°C above ambient, for 100 mW/cm^2 irradiation, free convention cooling (after brochure from Applied Solar Energy Corporation (5))

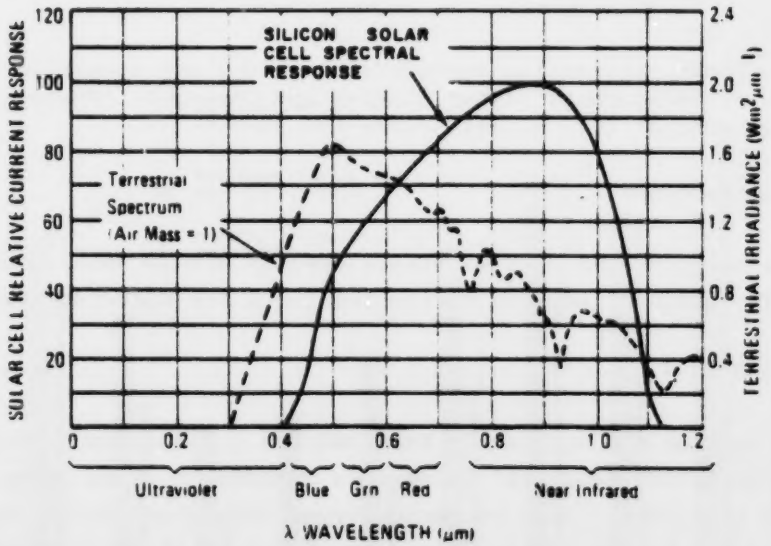
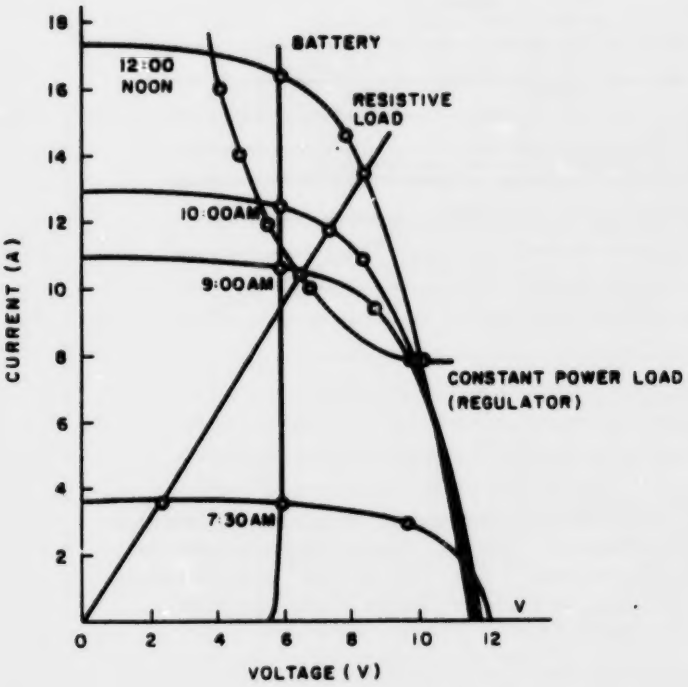


Fig. 6. Spectral response of a silicon solar cell (after brochure from Applied Solar Energy Corporation (5))



OBSERVATIONS

BATTERY

- BEST UTILIZATION AT 12 NOON

RESISTIVE

- POOR UTILIZATION AT 7:30 AM

CONSTANT POWER

- POOR UTILIZATION AT 12 NOON
- NEEDS OTHER POWER SOURCE AT 7:30 AM

Fig. 7. Power utilization consideratons - one day operation in terrestrial environment (after Bickler and Costogue, "Photovoltaic Cells and Arrays" (6), p. 51)

Material Imperfections

Some of the problems with materials used in module manufacture (American and Canadian) noticed during the tests are discussed below.

Module Terminal Box

- Some modules did not have a terminal box. Module connections were made with "AMP-Solarlok" connectors crimped to wires 46 to 61 cm (1 to 24 in.) long. Some connector types were glued to the back of th module and became loose after a short period of use. Some modules had two wires; others had four wires, one pair for parallel connection. Space for blocking and shunt diodes had to be configured elsewhere in the array.

- Some modules had an aluminum, ABS, or a PVC plastic terminal box (some of them waterproof). The aluminum boxes became easily frozen during winter and could not be opened easily. The screws holding

the covers of the terminal boxes were in some cases of mild steel. These rusted quickly when the modules were mounted in the open air.

Cover Glass

- Some modules had a smooth or a textured cover glass. When mounted in the open air, the latter type was found to require cleaning more often to remove trapped dirt.

- Some modules were found to have cracks in one corner a few days after installation. This may be due to assembly methods which did not allow for uneven expansions in the module frame and cover glass.

Measurement of Global Solar Radiation

Figures 8, 9, and 10 correspond to Tables 2, 3, and 4, respectively. From Figs. 8 and 9, it can be seen that the NRC measurements over a short (and restricted) period of one year using a silicon solar cell with a

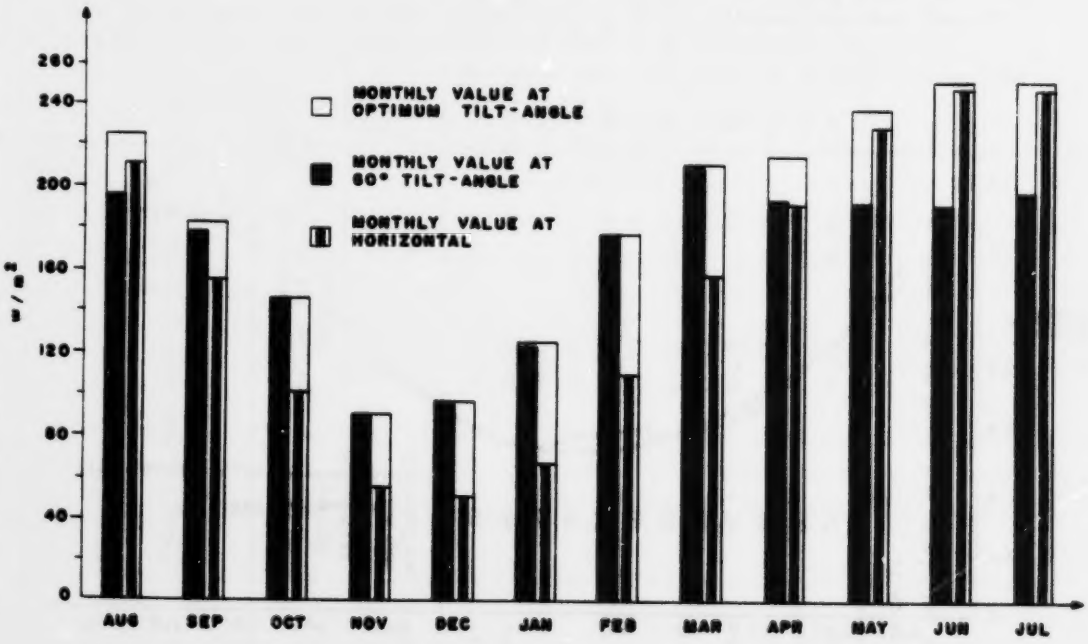


Fig. 8. Mean monthly values of daily short wave radiation (direct, diffused and reflected) on 0° aspect-angle and tilt-angles of 0° and 60° for Ottawa (latitude 45.5° North) from June 1957 to Dec. 1975

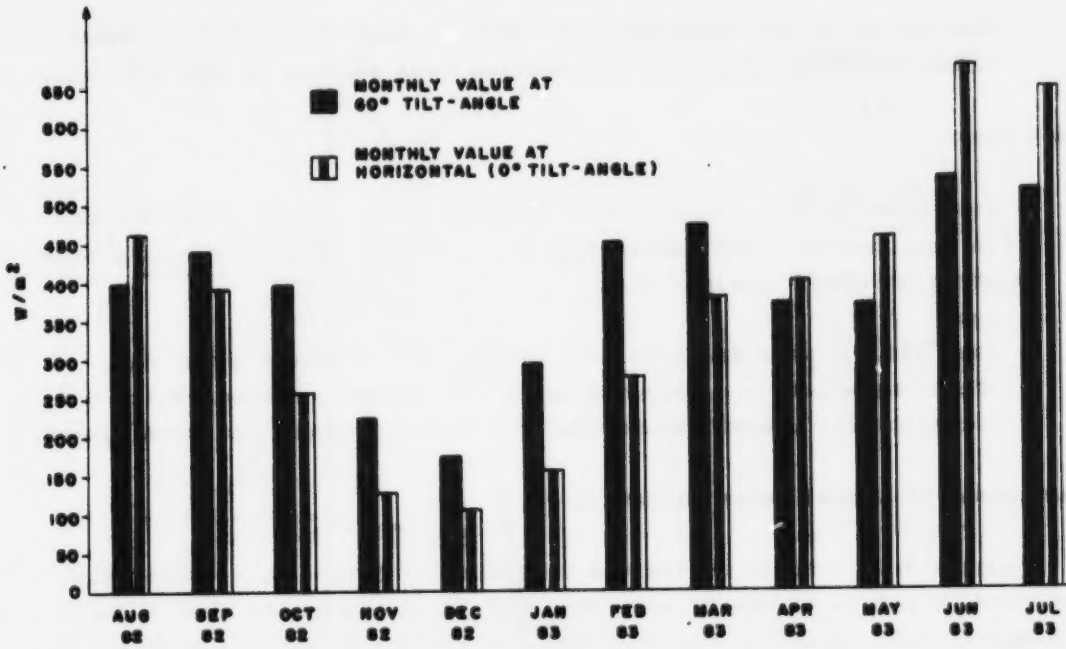


Fig. 9. Mean monthly values of daily short wave radiation (direct, diffused and reflected) on 0° aspect-angle and tilt-angles of 0° and 60° for Ottawa (latitude 45.5° North) from August 1982 to July 1983 (NRC measurements during the test period)

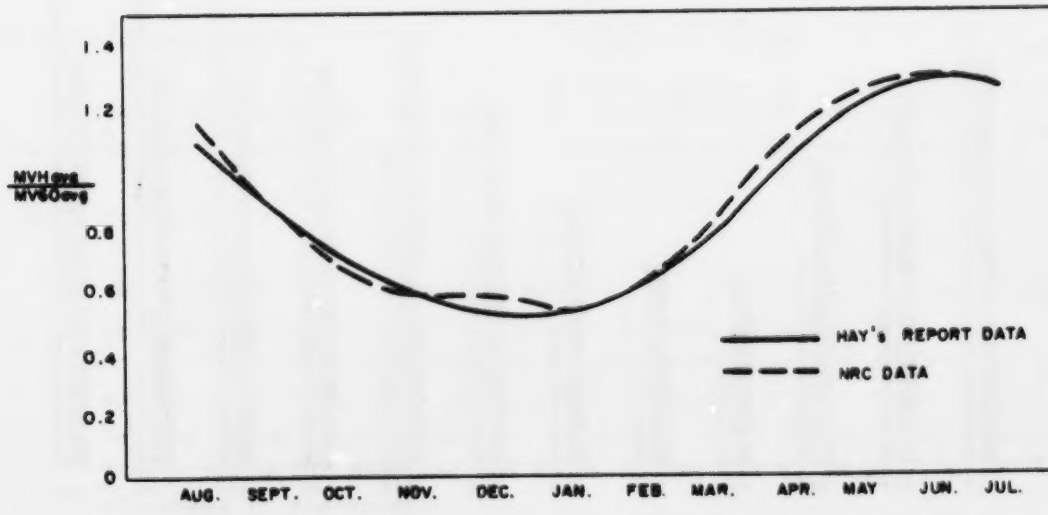


Fig. 10. Ratio of mean monthly values of daily short wave radiation on horizontal to 60° tilt-angle surface for Ottawa. Notes: NRC data, Aug. 1982 to July 1983; Hay's data (3), June 1957 to Dec. 1975

Table 2. Mean monthly values of daily short-wave radiation (direct, diffused, and reflected) on 0° aspect-angle and tilt-angles of 60° and 0° (horizontal) for Ottawa (latitude 45.5° N). From June 1957 to Dec. 1975.

Month	Optimum tilt-angle (°) (degrees from horizontal)	Monthly value at optimum tilt-angle (MWOPavg)		Monthly value at horizontal (MWHavg)		Gain (%) at 60° compared to horizontal MW60avg - MWHavg / MWHavg	Monthly value at 60° tilt-angle (MW60avg)		Gain (%) at 60° tilt-angle[b] MW60avg - MWOPavg / MWOPavg
		MJ / m^2 d	W / m^2	MJ / m^2 d	W / m^2		MJ / m^2 d	W / m^2	
January	70	10.90	126.11	5.77	66.76	86.48	10.76	124.49	- 1.28
February	60	15.38	177.95	9.44	109.22	62.92	15.38	177.95	0.00
March	50	18.32	211.96	13.76	159.20	31.61	18.11	209.53	- 1.15
April	30	18.60	215.20	16.68	192.99	0.84	16.82	194.61	- 9.57
May	20	20.51	237.30	19.92	230.47	-16.21	16.69	193.10	-18.63
June	10	21.73	251.42	21.47	248.41	-23.06	16.52	191.14	-24.00
July	10	21.81	252.34	21.41	247.71	-20.27	17.07	197.50	-21.73
August	30	19.41	224.57	18.17	210.23	-7.20	16.86	195.07	-13.13
September	40	16.19	187.32	13.40	155.04	15.00	15.41	178.29	- 4.82
October	50	12.63	146.13	8.69	100.54	44.76	12.58	145.55	- 0.40
November	60	7.75	89.67	4.68	54.15	65.60	7.75	89.67	0.00
December	70	8.34	96.49	4.37	50.56	88.33	8.23	95.22	- 1.32

[a] Reference 7.

[b] Gains calculated are based on the ratio of 60° and optimum tilt-angles.

Table 3. Mean monthly values of daily short-wave radiation (direct, diffused, and reflected) on 0° aspect-angle and tilt-angles of 0° (horizontal) and 60° for Ottawa (latitude 45.3° N) from August 1982 to July 1983 (NRC measurements)[a]

Month	Insolation at 60° (W/m^2)	Insolation at horizontal (W/m^2)
August 1982	400	460
September 1982	440	390
October 1982	390	260
November 1982	220	130
December 1982	180	100
January 1983	290	150
February 1983	450	270
March 1983	470	380
April 1983	370	400
May 1983	370	460
June 1983	530	680
July 1983	520	650

[a] Insolation data are based on measurements taken each working day per month between 08:30 and 16:00 hours. Silicon photovoltaic cell meters (NRC designed, Hollis Model NR5, and Haenni Model 118) used for measurements.

response, as shown in Fig. 6, follow in trend the measurements of Hay (3), which were taken over a period of about eighteen years (wavelengths of ~0.28 to 3 μm). Indeed, when the ratio of horizontal to 60° tilt-angle is compared between the two measurements (as shown in Fig. 10) and Table 4 the agreements are very close. From Table 3, it can be seen that for the described experiment for Ottawa, a tilt-angle of 60° provides an average of ~45% higher power density level from September to March over horizontal (or 0° tilt-angle).

Module Power Output

Module Physical Characteristics (Table 5)

The physical characteristics, e.g., total cell area, cover glass light transmission ratio, cell back plane material, of a PV module are all important because they affect the power output of the module. Hence, for

Table 4. Ratio of mean monthly values of daily short wave radiation on horizontal surface (MWHavg) to 60° tilt-angle surface (MW60avg) (both for 0° aspect-angle) for Ottawa (latitude 45.5° N)

Month	MWHavg/MW60avg ratio	
	NRC measurements[a]	Data from Hay (3)[b]
August	1.15	1.08
September	0.88	0.87
October	0.66	0.69
November	0.58	0.60
December	0.58	0.53
January	0.53	0.54
February	0.61	0.61
March	0.81	0.76
April	1.08	1.00
May	1.26	1.19
June	1.28	1.30
July	1.26	1.25

[a] NRC data based on measurements (restricted hours) taken over the period from August 1982 to July 1983.

[b] Hay's report data based on measurements taken over the period from June 1957 to December 1975.

any critical statistical comparison of module power outputs, all the physical characteristics that influence the power output of the module must be considered.

Module Operational Characteristics (Table 6)

The Canadian and American manufactured modules mounted on the roof of the mini-lab were monitored daily and the results are as shown. The characteristics that are prominent in the table are:

- the measured power output of most Canadian modules is much lower than their maker's rated values even though the measurements were taken at a lower temperature (~11°C).

- some American-made modules appear to show a trend similar to the point above.

- the deviation ratio in power output ratings of Canadian modules between the maker's and NRC values (columns 3 and 4, respectively are high because the modules are from the first or second generat of production. However, modules of recent manufacture (a6 and b1 show a noted improvement.

- the deterioration of power output between values at the beginning and the end of the test under similar conditions of load, tempera ture, and irradiance is larger among the Canadian modules of earl generation.

Since the maker's specifications do not clearly state their module t conditions (i.e., sun or simulator insolation and cell or ambient temper ture) when measuring the power output rating, it is difficult to conclud the level of deterioration. However, if the difference between the modu power outputs at the beginning and end of the test period is considered, i.e., column 7, it can be seen that there is an appreciable loss of powe output in certain Canadian modules of earlier generation, e.g., b5, b8, c6, c7, c8, and c9.

Average Energy Output (Figs. 11 and 12 and Table 7)

Two modules (Canadian and American) of similar power rating and oth specifications (Tables 2 and 3) were compared under identical operations conditions for each month of the year. It is observed that they continu to perform equally well. It is to be noted that the modules are not ful identical in their physical characteristics. The difference in their po output could be because of

- cell conversion efficiency, the American module is rated at 37 W the Canadian module is rated at 36 W

- the light transmission ratios of the cover glass of the modules

- the rate of heat dissipation from the back plane of each module

There may be also other different physical characteristics between modules.

Table 5. Module physical characteristics

Company[a]	Length (in.)	Length (cm)	Width (in.)	Width (cm)	Number of cells	Cell diameter (in.)	Cell diameter (cm)	Backing: Metal	Backing: Plastic	Cover glass: Smooth	Cover glass: Textured
A - a1	22.5	57.2	18.5	47.0	36	3	7.6	x		x	
A - a6	40	102	15.75	40.0	36	4	10.2		x	x	
B - b1	35.5	90.2	10	25	32	3	7.6		x		x
B - b2	35.5	90.2	10	25	32	3	7.6		x		x
B - b3	30	76	12	30	36	3	7.6	x		x	
B - b14	48	122	12	30	35	4	10.2		x	x	
C - c1	30	76	15.5	39.4	72	2	5.1	x			x
C - c2	21.25	54.0	16.75	42.5	72	2	5.1	x			x
C - c3	30	76	15.25	38.7	72	2	5.1		x	x	
U - m	48	122	12	30	35	4	10.2		x	x	
U - n	21	53	21	53	36	-[b]			x		x
U - p	44	112	17	43	36	4	10.2		x	x	
U - q	30	76	12	30	36	3	7.6	x			x

[a] A, B, and C - Canadian; U - American.
[b] Rounded corner "square cells" 3.34 in. × 3.34 in. (8.48 cm × 8.48 cm)

Table 6. Module operational characteristics (at beginning and end of test period 1980-1983)

(1) Company[a]	Code	Date of installation	(2) Test period (mo)	(3) Maker's max. power output rating[b] (W) at °C	(4) NRC measured output power At beginning of test	(5) NRC measured output power At end of test	(6) Percentage deviation[d]	(7) Percentage deterioration[e]	(8) Remarks[f]
A	a1	10/80	38	18/28°	14.67	14.64	-18.5	-0.2	Operational
A	a2	10/80	38	18/28°	16.49	16.20	-8.4	-1.8	Operational
A	a3	10/80	38	18/28°	17.34	16.9	-3.7	-2.5	Operational
A	a4	10/80	30	18 -	17.69	17.59	-1.7	-0.6	Operational
A	a5	10/80	26	18/28°	18.72	18.03	+4.0	-3.7	Operational
A	a6	11/82	13	32/28°	31.55	-	-1.4	-	Sun Tracker
B	b1	10/80	38	18 -	17.26	16.05	-4.1	-7.0	Operational
B	b2	10/80	38	18 -	11.36	-	-	-	Battery charging
B	b3	10/80	38	18 -	14.54	13.52	-19.22	-7.0	Operational
B	b4	10/80	38	18 -	17.33	16.03	-3.7	-7.5	Operational
B	b5	10/80	38	18 -	15.12	6.79	-16.0	-55.1	Battery charging
B	b6	10/80	38	18 -	17.53	16.84	-2.6	-3.9	Operational
B	b7	10/80	38	18 -	18.17	16.82	+1.0	-7.4	Operational
B	b8	10/80	38	18 -	17.81	11.41	-1.0	-42.1	Operational
B	b9	10/80	38	18 -	19.05	16.19	+5.8	-15.0	Operational
B	b10	10/80	38						Accidently damaged
B	b11	10/80	11	18 -	11.48	9.7	-36.2	-15.5	Battery charging
B	b12	10/80	36	18 -	14.88	14.51	-17.3	-2.5	Operational
B	b13	10/80	36	18 -	15.86	15.69	-11.9	-1.1	Operational
B	b14	7/82	11	36/28°	37.58	35.79	+4.9	-4.76	Sun Tracker
C	c1	1/81	5	14.4/28°	13.17	13.0	-8.5	-1.3	Operational
C	c2	1/81	26	14.4/28°	11.44	7.29	-24.7	-36.3	Operational
C	c3	1/81	26	14.4 -	13.15	10.49	-8.7	-20.2	Operational
C	c4	1/81	26	14.4 -	14.32	10.68	-3.8	-25.4	Operational
C	c5	1/81	26	14.4 -	12.50	10.07	-13.2	-19.4	Operational
C	c6	1/81	5	14.4 -	10.75	3.12	-22.6	-61.7	Battery charging
C	c7	10/81	0.5	14.4 -	12.7	4.5	-11.8	-64.6	Battery charging

Table 6 (Concluded)

(1) Company[a]	Code	Date of installation	(2) Test period (mo)	(3) Maker's max. power output rating[b] (W) at °C	(4) NRC measured output power At beginning of test	(5) NRC measured output power At end of test	(6) Percentage deviation[d]	(7) Percentage deterioration[e]	(8) Remarks[f]
C	c8	10/81	0.5	14.4 -	12.46	3.2	-13.5	-74.3	Battery charging
C	c9	10/81	5	14.4 -	14.3	0.5	-0.7	-96.5	Battery charging
U	m1	10/81	26	37/25°	39.28	39.00	+6.2	-0.71	Operational
U	m2	10/81	26	37/25°	38.3	36.64	+3.5	-4.33	Operational
U	n1	10/81	26	34/25°	28.32	27.45	-16.7	-3.1	Operational
U	n2	10/81	26	34/25°	27.98	27.42	-17.7	-2.0	Operational
U	p1	10/81	26	35/28°	36.52	36.26	+4.3	-0.70	Operational
U	p2	10/81	26	35/26°	37.28	37.21	+6.5	-0.20	Operational
U	q	10/81	26	23/28°	23.18	23.0	+0.8	-0.78	Operational

[a] A, B, and C - Canadian; U - American.

[b] The maker's maximum power output rating (column 3) whenever specified is for 1000 W/m^2 and an ambient temperature of 28°C, except for two American-made modules where the temperature is specified as cell temperature, e.g., 25°. The spectrum (sun or simulator) was not specified by the maker when the maximum output power rating was given.

[c] NRC measured output power at beginning and end of the test period is given for ~1000 W/m^2 solar spectrum and ~41°C ambient temperature.

[d] Percentage deviation is based on columns 3 and 4.

[e] Percentage deterioration is based on of columns 4 and 5.

[f] Operational - module still located on the roof of the mini-lab; sun tracker - module transferred to sun tracker frame; battery charging - module transferred to battery charging operation.

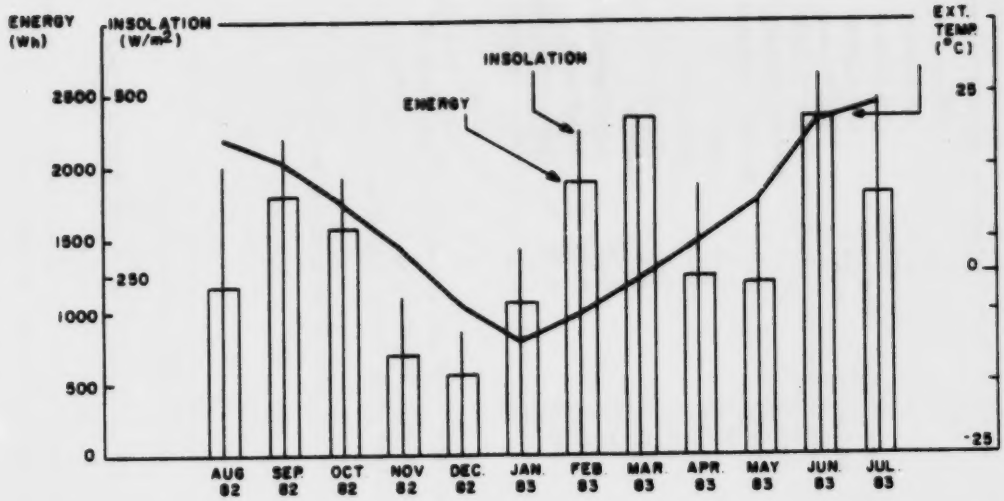


Fig. 11. Monthly average energy output of a Canadian manufactured PV module in Ottawa. Notes: Module installed at 60° tilt-angle. Module specifications: power rating, 36 W; total cell area, 0.2837 m^2 (81.07 cm^2/cell)

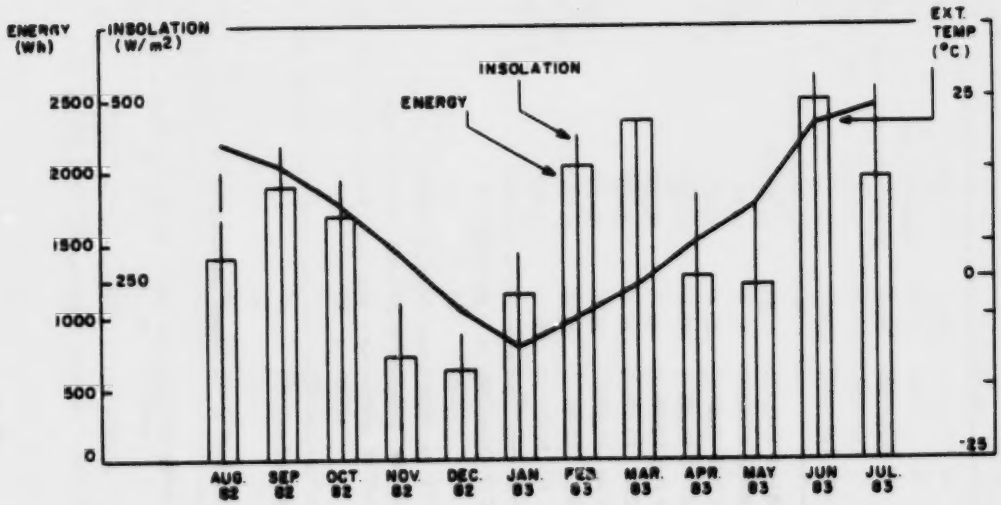


Fig. 12. Monthly average energy output of an American manufactured PV module in Ottawa. Note: Module installed at 60° tilt angle. Module specifications: power rating, 37 W; total cell area, 0.2837 m^2 (81.07 cm^2/cell)

Table 7. Average energy output comparison between a Canadian (B-b14) and an American (U-m2) manufactured module of similar size and under similar test conditions[a,b,c]

Month	Energy[d] (Wh) American	Energy[d] (Wh) Canadian	Average insolation 60° tilt (W/m^2)	Average external temp. (°C)
August 1982	1400	1160	400	19
September 1982	1900	1790	440	16
October 1982	1690	1570	380	10
November 1982	730	700	220	4
December 1982	630	560	180	-5
January 1983	1150	1060	290	-9
February 1983	2030	1900	450	-5
March 1983	2340	2350	470	-1
April 1983	1270	1260	370	5
May 1983	1220	1200	530	11
June 83	2490	2350	530	22
July 1983	1960	1820	520	23

[a] Total cell area of each module ~0.28 m^2 other physical characteristics given in Table 2 under B-b14 and U-m2.

[b] Data acquired during 8:30 to 16:00 h for each working day of the month only.

[c] Load resistance of the module adjusted for maximum output power around the 21st day of each month at solar noon.

[d] Watt-hour calculations are based on the daily average load voltage (see [b] above) and the monthly adjusted value of load resistance (see [c] above). (See also columns 8 and 10 in Table 1 for each module.)

OBSERVATIONS

(1) From the manufacturers' specifications, both American and Canadian, the dimensions, and the electrical ratings, e.g., peak power output, voltage and current at peak power, series resistance and nominal operating cell temperature of the modules are not yet well standardized.

(2) Of the 39 Canadian modules at the beginning of the test period, 9 were returned to the makers because of serious defects, 29 survived the test period, and 1 was accidentally damaged.

Canadian

Company A: Total number of modules 9
- 6 modules (a1 to a6) were found to have less than 5% power output deterioration level over the test period.
- 3 modules were transferred to battery charging operation, because of reduced power output of about half of the rated value. These are not included in Table 6, as they were some of the very first generation modules.

Company B: Total number of modules 17
- 4 modules (b6, b12, b13, and b14) were found to have less than 5% power output deterioration over the test period.
- 3 modules were found defective and were returned to the supplier. These are not included in Table 6 as they were some of the very first generation modules.
- 6 modules (b1, b3, b4, b7, b8, and b9) were found to have ~7 ~7 to 42% output power deterioration level over the test period.
- 3 modules (b2, b5, and b11) were transferred to battery charging operation due to reduced power output of about hali of the rated value.
- 1 module (b10) was accidentally damaged during tests.

Company C: Total number of modules 13
- 1 module (c1) was found to have less that 5% power output deterioration over the test period.
- 8 modules (c2 to c9) were found to have a deterioration in power output level from ~19% to ~96%.
- 4 modules (of the 8) (c6 to c9) were transferred to battery charging operation due to reduced power output of about hali the rated value.
- 4 modules were found defective on initial testing and were returned to the supplier. These are not included in Table

It is to be noted that some of the earlier (1980/1981) manufactured Canadian modules, e.g., a1 to a5, b6, and c1 showed less than ~4% in power output deterioration.

American

Company U: Total number of modules 7
- All 7 modules indicated less than 5% power output deterioration.

When analysing the above-quoted performance deficiencies of the Canadian-made modules, the following should be taken into account:

- the recent initiation of the PV technology in Canada (~1978)
- lower capital investment in Canada
- less sophisticated fabrication methods used in Canada

The two modules compared in Figs. 11 and 12 indicate that the Canadian module performed equally as well as the American module in spite of the reasons given above. The results of this study cannot be used for any statistical evaluation of module performance, because of the different types and manufacture of modules. However, the performance of the modules under the prescribed test conditions points out their significant characteristics which may be useful for further design analysis.

CONCLUDING REMARKS

The "hands-on" experience provided by the study has been valuable for work in PV power system design. Some of the experiences gained on the operational characteristics of PV modules under actual conditions of varying load, insolation, and temperature have been useful in the design of a stand-alone 50 Wp photovoltaic power system (7) for field use.

The tilt-angle of the module at the latitude of location plays a key role in determining the available electrical output during different months of the year. This change could be matched with load requirement pattern to economise in the number of modules and amount of electrical storage capacity, if any, for a given system. Relatively, a fixed tilt-angle with 0° aspect angle appears to be the most economical and simple in array structure.

Considering the time frame between development and production, the sophistication of processing equipment and the production environment (clean room standards), the Canadian modules can be nonetheless comparable in performance and reliability with those of American manufacture. However, an improvement in processing technique, equipment, and manufacturing environment is essential for better product performance and reliability. Further, a strict quality control of specifications and processes during manufacture of the modules is mandatory for their long term high performance and reliability.

ACKNOWLEDGEMENTS

The authors wish to thank Drs. M. Buchanan and S. Karius of the Division of Energy, NRC, for discussions on the preliminary draft of this report. The Division of Energy has partly funded this project. Thanks are also due to a Co-op Student from the University of Sherbrooke, Yves St. Sauveur, for data manipulation and graphic plots.

REFERENCES

1. Solar Cell Array Design handbook Vol I, California Institute of Technology. U.S. DOE N77 - 14193. October 1976.

2. Block V Solar Cell Module, Design and Test Specification for Intermediate Load Applications. U.S. DOE-JPL-5101-161. 1981.

3. Hay, J.E. Analysis of solar radiation data for selected locations in Canada. Climatological Studies No. 32. Fisheries and Environment Canada. October 1977.

4. Mobil Tyco Solar Energy Corp., Data Ra 40. Company product data.

5. Applied Solar Energy Corp., Data P017 2/82 1.5M 1982. Company product data.

6. Bickler, D., and Costogue, E. Photovoltaic cells and arrays. Calif. Inst. Technol., Jet Propul. Lab., JPL Q. Tech. Rev. 1976.

7. Ayer, J. Design of a stand alone photovoltaic power system. Proc. 16th IEEE PV Specialist, San Diego, CA. September 1982.

APPENDIX A. TEST FACILITY COMPONENTS

1. Data acquisition and control system Analog Devices Ltd., Model Macsym 2.

2. Insolation monitors:

   RHO Sigma Model 1008
   NRC designed (solar cell)
   Haenni Model 118
   Eppley Pyranometer Model 8-48 → for reference
   Hollis Model MR-5

3. Meteorological monitors:

   Temperature
   Relative humidity } NRC built
   Wind speed and direction

4. Electrical measurements

Electronic dc wattmeter	NRC designed
Voltmeter	Fluke Model 8010A
Ammeter	Fluke Model 8010A

APPENDIX B. NOMINAL ACCURACY OF THE MEASURING INSTRUMENTS

Peak dc watts	±1.0% at 50 W range
Open circuit dc volts	±0.1% + 1 count
Short circuit dc current	±0.5% + 1 count
Temperature	±0.5°C below 0°C ±2°C above 10°C
Relative humidity	±5%
Time	±1 min